Arunas P. Kuciauskas
6/13/99

Tracking Tropospheric Aerosols across the Pacific Ocean

1. Introduction

In the study of cloud physics, aerosols serve as condensation nuclei toward the formation and persistence of clouds. In climatology, aerosols affect the radiation budget of the atmosphere by the scattering and absorption of solar and thermal radiation within clear and cloudy conditions. A change in background aerosol distributions during events such as volcanic eruptions, increased anthropogenic emissions (pollution and deforestation) and dust storms will directly impact cloud coverage, precipitation events and air quality not only over source regions but in areas far downwind.

Throughout the troposphere, aerosols greatly vary in size and distribution. Modeling efforts to assess and predict synoptic conditions have often been hampered due to improper usage of aerosol distributions over the region of interest, particularly over data-sparse regions such as the Pacific Ocean. Until recently, measurements of aerosol distributions have been nearly impossible, confining the research to applying global average amounts on a global scale. Fortunately, recent developments have greatly improved the accuracy of determining aerosol concentrations and properties. These include the development of a global network of ground-based sun photometers, aerosol retrieval models from polar-orbiting satellite data, and improved optical depth models extracted from weather prediction models. Researchers at the Naval Postgraduate School (NPS) and the Naval Research Laboratory (NRL) are conducting research in ongoing field studies and aerosol detection models which should greatly improve the knowledge-base of aerosol distributions and properties.

This paper will demonstrate the ability of satellite retrieval products and numerical weather prediction models to track dust/aerosol plumes whose concentrations are well above background levels. The region of interest is over eastern Asia and the northern Pacific Ocean, since the Gobi desert within Mongolia and western China, as well as the density of urban-related pollution emissions supply a wealth of aerosol plumes. The passage of these plumes can then be tracked over the Pacific Ocean, whose air mass is relatively uniform, providing a simpler environment for aerosol tracking.

2. Aerosol distributions over the Pacific Ocean

2.1. General characteristics

One of the traditional methods for obtaining aerosol concentrations is through an Aitken nucleus counter. Based on this technique, Wallace and Hobbs (1977) reported typical aerosol particles ranging from $10^3 cm^{-3}$ over the ocean, to $10^4 cm^{-3}$ over rural land areas, to $10^5 cm^{-3}$ or higher in polluted air over urban areas. Most of the aerosols are generated at surface level. Over the desert and low sparse grassland regions in Mongolia and western China, high surface wind speeds can inject enormous plumes of dust high into the atmosphere. Upper level westerlies then transport these plumes at great distances over the Pacific Ocean basin before being depleted by rain, coagulation processes, and/or gravity.

Figure 1 displays typical aerosol size distributions for a number of environments and source regions. The Pacific Ocean background, positioned toward the center of the chart, describes the marine environment far removed from land. Aerosol diameters vary between .01 to 10 microns. The introduction of an Asian plume event produces a profile along the red curve, as shown. The profile is the author's conception and based somewhat in accordance with results presented by Hoppel, et al. (1986) for aerosol distributions within non-precipitating clouds. The modified aerosol profile practically spans the entire aerosol size spectrum with one exception, the profile doesn't begin at the smallest sizes because of coagulation processes for aerosols below .01 microns due to coagulation processes, once the plume moves awau from its source. According to Hoppel (1986), there is a bi-modal distribution within the accumulation stage between .01 - 1 micron diameter sizes. The first peak represents coagulation proceses within dry aerosols while the second peak immediately to the right represents cloud processes, mainly in the form of coalescence. Studies

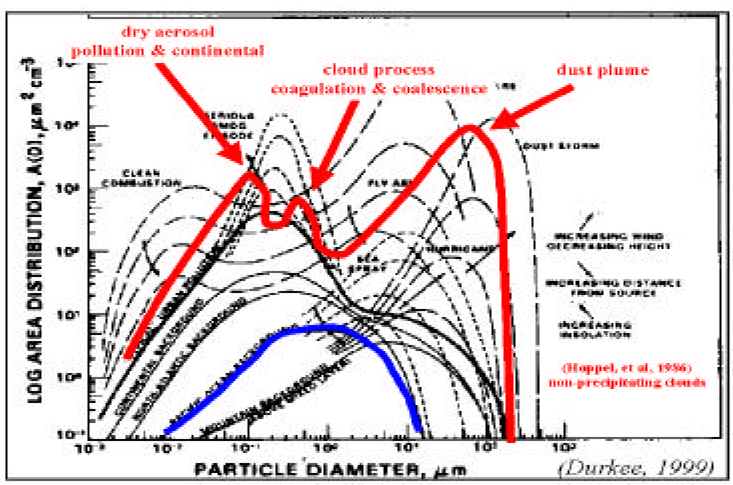


Figure 1. Aerosol spectra showing background aerosol distributions. The blue contour depicts typical pacifc ocean aerosol distribution. The red contour depicts the author's conception of aerosol distribution during an Asian dust storm event. (from Rogers and Yau, 1996)

have shown that these peaks are typically distinct; during the coalescence process within clouds, nuclei are clumped together. During the evaporation process, the nuclei remain clumped together, thus accumulating a higher number of aerosols within that diameter. On the large aerosol size range, the dust plumes which orinate within the Gobi desert provide the third peak within the 10 - 1000 micron aerosol size range.

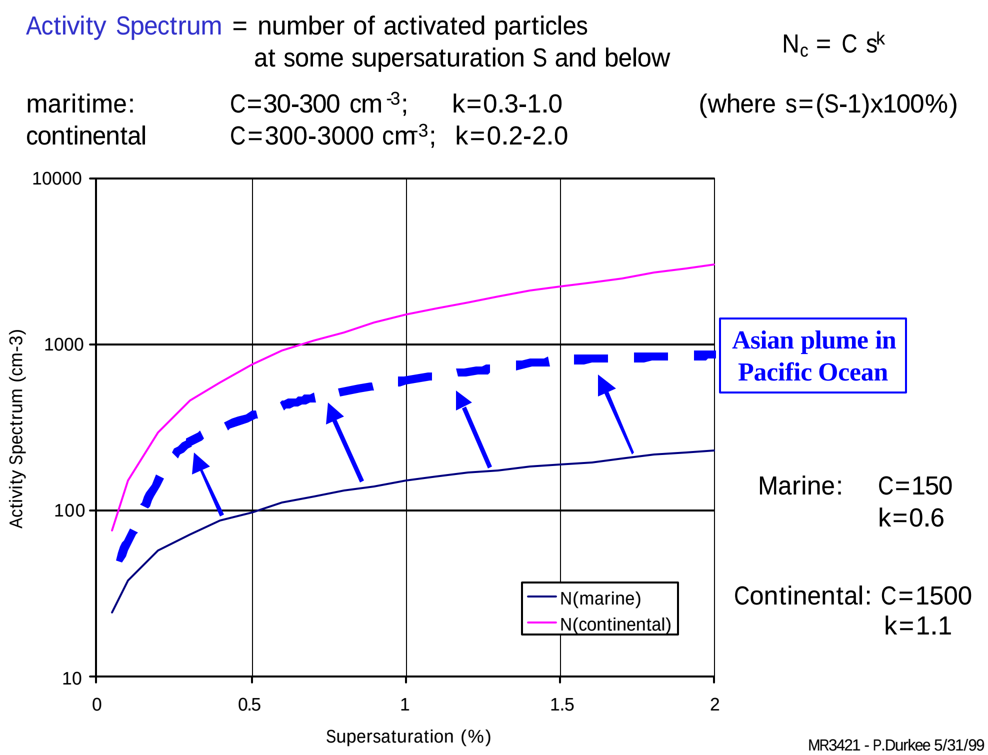


Figure 2. Activity spectrum of maritime and continental particles as a function of supersaturation. Dashed blue line indicates higher levels of particles from maritime conditions during Asian dust storm event. (from Durkee)[1]

Figure 2 presents the activity spectrum of aerosols particles which serve as cloud condensation nuclei for the various supersaturations. The typical maritime and continental profiles are profiled. Also shown is the expected profile during an Asian plume outbreak, where the aerosol distribution nad its associated activated nuclei would be expected to grow from maritime conditions to a profile possibly exceeding the continental profile, especially within dry air or non-precipitating clouds. As a result, aerosols within the Asian dust plume event would be expected to provide a rich source of CCN, resulting in an increase in cloud coverage, with cloud

[1] http://www.nps.navy.mil/~durkee/MR3421/MR3421.htm

droplets being smaller and assuming more continental characteristics to the cloud's microphysical and radiative properties.

2.2. Satellite sensing of aerosols

Satellites provide information about aerosol concentrations and size distributions on a global scale. This can be accomplished by measuring atmospheric extinction which includes both scattering and absorption of sunlight by aerosol particles. The extinction coefficient is defined by:

$$\sigma_{ext} = \int_0^\infty \pi r^2 Q_{ext}(m,r)\, n(r)\, dr$$

where r is the particle radius, πr^2 is the particle cross-sectional area, $Q_{ext}(m,r)$ is the extinction efficiency factor, which is a function of both the composition and size of a particle, m is the complex index of refraction, and n(r) is the numbre of particles for a given radius. Changes in the size, composition, or distribution of the particles effect the amount of extinction observed. By integrating the equation, optical depth is obtained. Figure 3 provides a pictorial

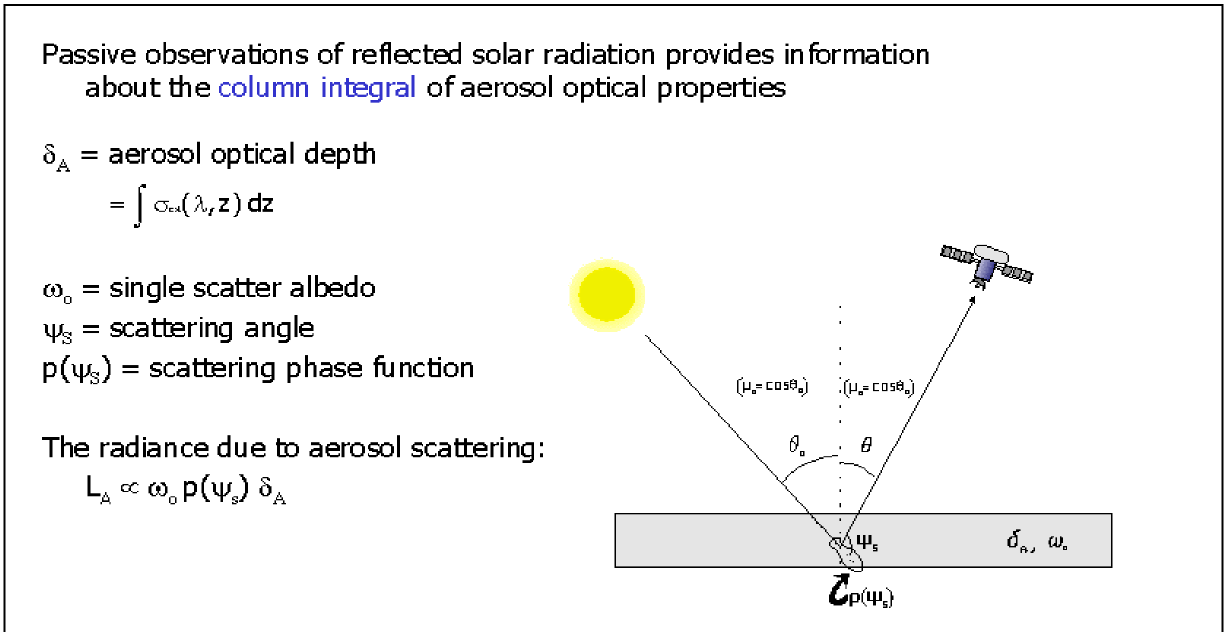


Figure 3. Pictorial representation of aerosol optical depth and resulting satellite radiance calculation. (from Durkee notes for MR 3522)[2]

[2] http://www.nps.navy.mil/~durkee/MR3522/MR3522.htm

representation of optical depth, which leads to satellite-sensed radiance, as shown. The radiance equation can be applied to a cloud-free marine environment, where multiple scattering is negligible. Optical depth is the common parameter used to measure aerosol concentration by weather satellite sensors as well as ground-based sun photometers.

3. Methods of tracking aerosols

Much of the material for this report comes from NRL's aerosol website, which provides an assortment of aerosol observations, aerosol modeling, satellite analysis and aerosol modeling. There is also a section that provides brief analyses during unusually high aerosol plume events during the past year. This report will focus on products of the following:

- NOGAPS: The Navy oceanographic and atmospheric prediction system: Surface weather reports furnished by Fleet Numerical Meteorological and Oceanography Center (FNMOC)
- NAAPS[3] - Navy Aerosol Analysis and Prediction System: Developed at NRL, this package is a global aerosol model which currently provides images of optical depths for a variety of aerosol sizes such as sulfate, dust, and smoke concentrations. NAAPS utilizes NOGAPS wind parameters, surface synoptic reports of weather and visibility, and aerosol data consisting of 60 sun-sky scanning spectral radiometers located globally.
- TOMS[4] - The total ozone mapping spectrometer: Developed at NASA's Goddard Space Flight Center, this satellite instrument is intended to sense and display global amounts of ozone. However, the .34 and .38 micron sensors on board the instrument are sensitive to aerosols from biomass burning, volcanic activity and mineral dust storms smoke and carbonaceous aerosols. Unlike the AVHRR, TOMS can detect these aerosols over land as well as open water, however, its spatial resolution is coarser (4 km) than the AVHRR (1 km).
- NPS aerosol retrieval model (Brown, B.B., 1997, Smith, P.J., 1998): Developed at NPS, this radiative transfer algorithm computes optical depth values from upwelling radiances as sensed from visible wavelengths onboard the NOAA polar orbiting AVHRR sensor. The algorithm masks out land, cloud and sun glint regions. The algorithm performed well when compared to ground truth instruments during recent aerosol measurement experiments.

[3] http://www.nrlmry.navy.mil
[4] http://windfall.evsc.virginia.edu/~class/Debbie/TOMS.html

4. Case study: Asian dust plume event from 14 - 29 March, 1998

4.1. Initial conditions

On 15 March, 1999, a fairly significant dust plume event occurred over western Mongolia, with reports of strong surface winds. In Figure 4, the encircled region lies within the Gobi desert, therefore, any strong wind event would eject large sand and dust particles into the atmosphere. Figure 5 shows a time series of surface observations located within the yellow square in Figure 4.

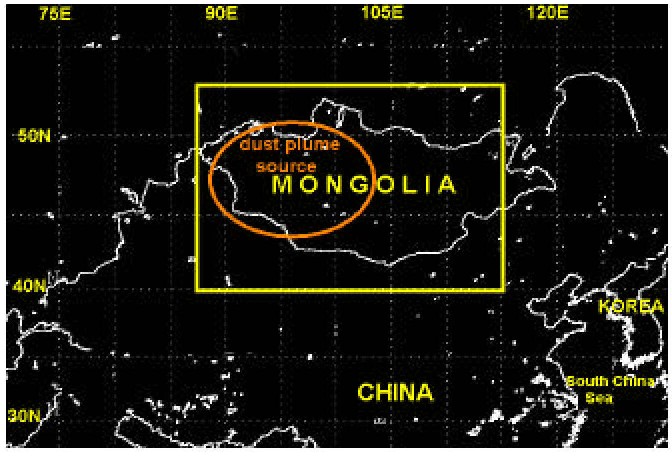
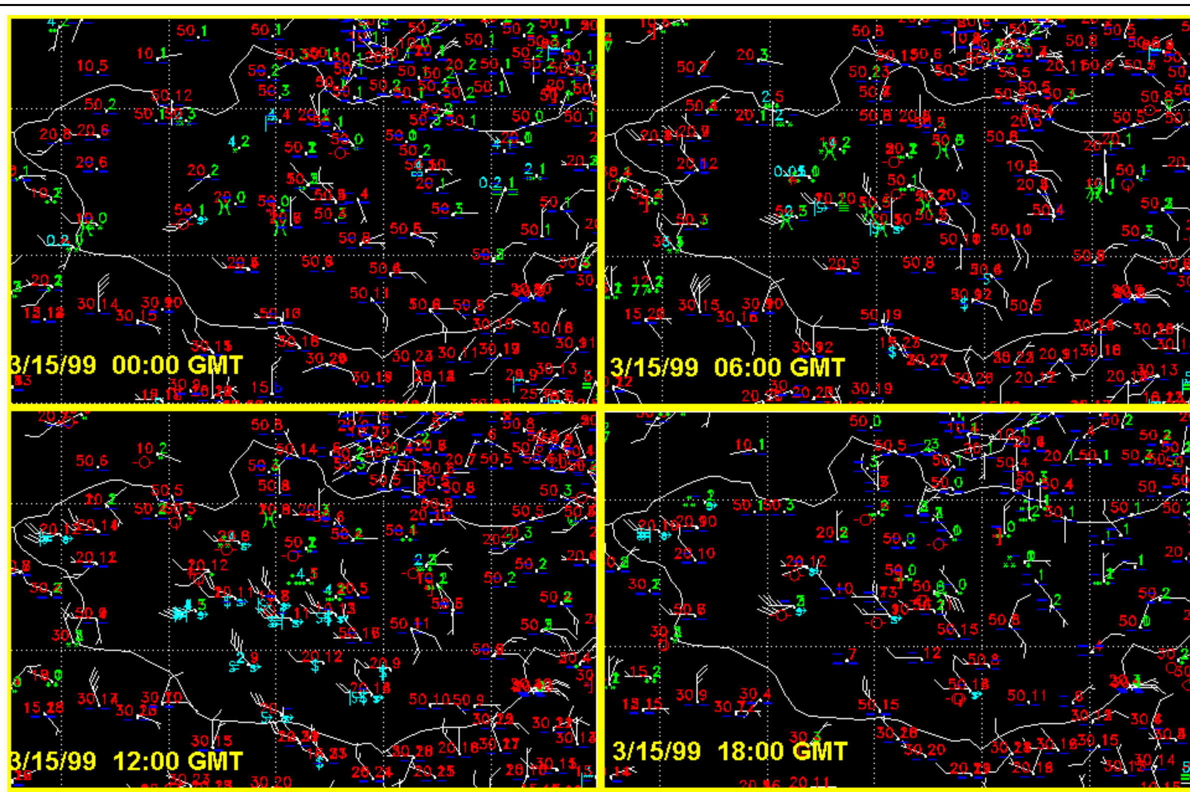


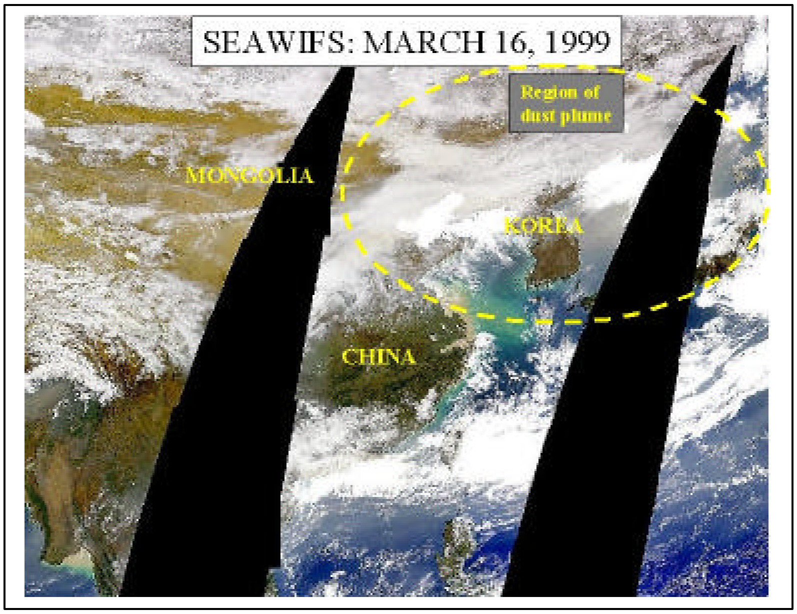
Figure 4. Map of Eastern Asia depicting the region of the dust plume onset. Yellow box corresponds to area of surface reports given in Figure 5.

Initially (15 March 00 GMT), the wind field was light and variable throughout western



Mongolia, but started to intensify with 40 kt westerly at 06 GMT. The strong wind event reached its maximum some time around 12 GMT with 40+ kt wind speeds reported over several stations. Surface winds subsided somewhat by 18 GMT. Extensive regions of blowing dust (marked in the color teal) were initially reported at 06, with a maximum at 12 GMT.

The satellite image in Figure 6 displays the position of the resultant dust plume (faint gray color) one day after the high wind event. As shown, the plume extended from eastern Mongolia through Korea and into the western Pacific Ocean. Dust can be seen toward the center and lower right of the image; its effects are minimal and unrelated to this case study.



4.2. Tracking the aerosol plume

Appendix A represents a time series of images that track the progress of the Asian dust plume across the Pacific Ocean. As shown, the images are comprised of TOMS aerosol index values and corresponding NAAPS aerosol optical depth values. Unfortunately, the TOMS output was not calibrated to provide optical depth measurements. As shown, there is generally good agreement between TOMS and NAAPS plots in identifying the positions of the dust plume concentrations propagating from eastern Asia. Between 17-20 March, the initial plume (blue colors) described above is shown propagating from the western to eastern Pacific Ocean and appears to reach the U.S. west coast by 21-22 March period. A second and more intense dust plume event occurred over eastern Asia around 21 March; the resultant plume is shown to propagate across the Pacific Ocean within the 23-24 March plots. The more significant concentration of dust appears to reach the U.S. West coast at the 27-28 March time plots.

Appendix B presents pairs of visible AVHRR images and corresponding optical depth plots from the NPS aerosol model, covering the eastern Pacific Ocean during 21-29 March, 1999. As described in Section 3, the optical depth data is only displayed over open water, and free of clouds and sun glint. These sets of images were used as an attempt to image the arrival of the Asian dust plumes over the eastern Pacific Ocean. Unfortunately, the region was constantly inundated with clouds and sun glint patterns. In addition, optical depth was suspect within cloud and sun glint edges. Nevertheless, some analysis can be attempted. On 21 March, with the arrival of the first dust plume over California, there appears to be some heightened optical depth values from background levels of ~0.1 (dark blue) to 0.2-0.3 (green) over the 130W, along the lower middle portion of the image. During the next several days, cloud cover and the sun glint made analysis impossible. One may speculate that with the second plume arrival on 27 March, there might have been some enhancement of optical depth values from background levels, but that would be optimistic speculation.

5. Conclusions

As presented, the TOMS and NAAPS products were shown to monitor high aerosol plumes in the form of dust particles from eastern Asia through the Pacific Ocean. The results from the NPS aerosol model were disappointing; cloud coverage and sun glint problems prevented any reasonable analysis.

For future studies, the addition of land-based sun photometers would provide ground truth data of optical depth. Although such data exists, the time span for calibrating and filtering the data set is quite lengthy.

This report did not address the interactions of aerosols with clouds during this case study; not much research has been conducted in the area of continental aerosol influences over maritime environments. However, in starting in the year 2000, an intensive four year research program over the western Pacific Ocean region will measure a variety of aerosol properties, including aerosol-cloud interactions. Known as ACE-Asia[5] (Asian Pacific Regional Aerosol Characterization Experiment), the program's general goal will be to study the radiative forcing due to anthropogenic aerosols over the Asian pacific region. This program will involve a network of ground stations to quantify the properties of aerosols, intensive field studies to

[5] http://saga.pmel.noaa.gov/

measure aerosol properties and processes, and research the effect of clouds on aerosol properties and vice-versa.

As part of his thesis work, the author will attempt to enhance the use of the NPS aerosol model by continuing the application of the model from polar-orbiting to geostationary satellites. This procedure will hopefully allow optical depth measurements to be viewed in a continuous time scale.

6. References

Brown, B.B., 1997: Remote measurement of aerosol optical properties using the NOAA POES AVHRR and GOES imager during TARFOX. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 73 pp.

Hoppel, W. A., G. M.Frick, R. E. Larson, 1986: *Effect of nonprecipitating clouds on the aerosol size distribution in the marine boundary layer,* Geophys. Res. Lett., **13**, 125-128.

Rogers, R. R. and M. K. Yau, 1996: *A short course in cloud physics,* Butterworth - Heinemann, Woburn, MA.

Smith, P.J., 1998: Remote measurement of aerosol optical properties using the NOAA POES AVHRR during ACE-1, TARFOX and ACE-2, M.S. Thesis, Naval Postgraduate School, Monterey, CA, 58 pp.

Wallace, J. M., and P. V. Hobbs, 1977: Atmospheric science, an introductory survey, Academic press, Inc., New York, NY.